SOLAR THERMAL ACTIVE SYSTEMS: FROM CLOSED FORM MODELS TO SIMPLE SIZING RULES FOR COLLECTOR CIRCUITS

Bernard BOURGES, Consultant
6, rue de l'Armor, 35760 St-Grégoire (France)

Jérome ADNOT, Centre d'Energétique, Ecole des Mines
60, Bd St-Michel 75006 Paris (France)

ABSTRACT

A simple closed-form model of thermal solar active systems (Space or Water heating) is presented. It deals both with fully-mixed storage and perfectly stratified storage and enables a better understanding of physical phenomena occurring within the system (e.g. low collector flow-rate effects). Direct application of this model makes it possible to establish partial sizing rules for the system components: storage capacity, storage insulation, pipe insulation, heat-exchanger area, collector flow-rate.

KEYWORDS

Solar heating; solar Domestic Hot Water; design; closed-form model; stratification; solar collector; storage; heat-exchanger; pipe loss.

INTRODUCTION

Active solar thermal system operation can still be improved; this involves physical phenomena introduced by "system effects" which are as yet insufficiently known. The so-called "low collector flow-rate" discussion over these last few years (Van Koppen, 1979; Fanney and Klein, 1986; Hollands and co-w., 1986) pointed out this fact. Detailed simulation programmes contributed in a large way to this improvement (Wuestling, 1985). Simpler models, e.g. closed-form, can also provide essential information. This concerns basis phenomena, like stratification, but has also practical consequences through various sizing rules for system components. This is a brief presentation of this type of simple model and some of its applications.

CLOSED-FORM MODEL

This model has been developed by Bourges and Adnot (1986). It is based on a number of usual linear thermal assumptions for each component: solar collector, heat-exchanger, storage heat loss, etc. The space-averaged storage temperature T is governed by the differential equation

$$M\,c\,dT / dt = A\,F_r'(n_0\,I - U_l\,(T_b - T_a)) - A_s U_s\,(T - T_e) - L \qquad (1)$$

The right-hand side of this equation includes three terms: collector energy output (controlled and therefore never negative); storage heat loss; energy taken from storage to meet the load. In the fully-mixed storage case, the bottom storage temperature, Tb, is simply the average temperature T. If the storage is perfectly stratified, Tb may be computed during one storage cycle from the initial conditions within the tank. The energy taken from the store may be computed in several ways according to the energy extraction type (Directly from the store or at collector outlet), but it is generally characterized by a draw-off flow-rate, m2.
The solution of eqn (1) in the "mixed case" involves the "system heat storage correction factor", introduced by Phillips (1981). This term is representative of daily system efficiency and characterizes the drawback of limited storage capacity as compared to an infinite capacity. In the most simple case (constant irradiance during collector operating time td, no draw-off, no losses), it takes the form:

$$G_{cst} = (1 - \mathrm{EXP}(-A\,F_r'\,U_l\,t_d / Mc)) \,.\, Mc / (A\,F_r'\,U_l\,t_d) \qquad (2)$$

This solution may be generalized to provide a stratified system for which an equivalent mixed system may be defined by introducing two stratification coefficients K1 and K2 (Bourges and Adnot, 1986) (Table 1).
The first one applies as a multiplicative factor both to Fr' and m2; the second one to storage heat loss. The following basic assumption is required: the storage water passes through the collector at least once during collector operating time (one storage cycle at least). Theoretically a whole number of cycles or passes is needed, but that has no effect for more than two cycles.

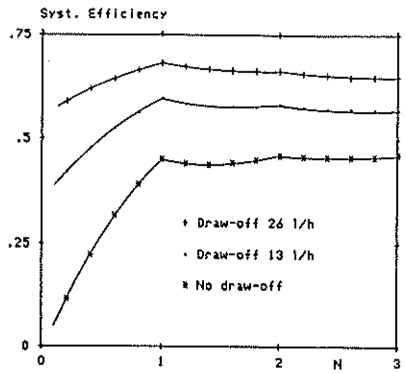
Table 1 Stratification coefficients vs $az = (1 - AF_r'U_l/m_1c_1)\,(1 - m_2/m_1)$

	$A_sU_s / m_1c_1z = 0$					$A_sU_s / m_1c_1z = 0.25$				
az	1.0	0.8	0.6	0.4	0.2	1.0	0.8	0.6	0.4	0.2
K_1	1.00	1.12	1.28	1.53	2.02	1.00	1.11	1.26	1.50	1.95
K_2	1.00	1.00	1.02	1.07	1.20	1.00	1.00	1.02	1.07	1.20

STRATIFICATION EFFECTS

It is well known that for thermosyphon or direct systems the collector flow-rate has no effect on daily efficiency if no draw-off occurs during the operating period (Gordon and Zarmi, 1981): the stratification coefficient K1 exactly compensates the decrease in the heat-removal factor Fr. If water is drawn-off from the tank during the day, an optimal collector flow-rate is observed; it corresponds to a single-pass system (one storage cycle during the collector operating time) (Wuestling, 1985; Fanney and Klein, 1986). This result can be illustrated with the solution to eqn 1 (constant irradiance) (Fig. 1): the larger the draw-off, the more important the performance improvement due to the low flow-rate as compared to an infinite rate.

Fig. 1: Daily system efficiency of a stratified system as a function of number of cycles (direct syst.)



STORAGE SIZING: MAXIMAL DAILY TEMPERATURE

The system heat storage factor (eqn 2) makes it possible to calculate the storage energy content at the end of the daily collecting period, and therefore the storage temperature if the solar irradiance is constant (no draw-off). It has been generalized (Bourges and Adnot, 1986) to cover other irradiance profiles, like a sine-shaped radiation (more realistic). Values are given in Table 2: they are a bit higher than for constant irradiance although the operating time is shorter, but differences are negligible as long as the operating period is less than half of characteristic time. This factor makes it possible to compute the maximal storage temperature for a given day with maximal irradiation Ht (and no-draw-off) from the initial temperature T0

$$E_s = A\ F_r'\ G\ n_0\ \emptyset\ H_t \tag{3}$$

Daily Utilizability, Ø, is computed at the threshold irradiance defined by initial temperature T0.

Table 2 System heat storage correction factor vs $x = Mc\ /(A\ F_r'\ U_l\ t_d)$ for constant (G_{cst}) and sine-shaped (G_{sin}) radiation

x	0.20	0.50	0.75	1.00	1.50	2.00	3.00	5.00
G_{sin}	.271	.493	.596	.664	.749	.800	.857	.910
G_{cst}	.199	.432	.552	.632	.730	.787	.850	.906

STORAGE AND PIPE INSULATION

Pipe and duct heat loss can be integrated in the collector characteristics, as proposed by Beckman (Duffie and Beckman, 1980). These formulas can be slightly modified and generalized by considering inlet and outlet pipes (with respective heat loss coefficients: AinUin, AoutUout) as heat-exchangers (with their own effectiveness). The modified collector loop characteristics can then be computed as follows

$$U_l^* = U_l + (A_{in}U_{in} + A_{out}U_{out})\ /\ A \tag{4}$$

$$n_0^* = n_0\ .\ \mathrm{EXP}\ (-\ A_{out}U_{out}\ /\ m_0c_0)\ .\ F_r\ /\ F_r^* \tag{5}$$

The effect of pipe heat loss on long-term system performance may be approximated for a given typical day by eqn 3. It is more important for stratified systems, with low collector flow-rate.

As stated by table 1, storage heat loss is slightly enhanced by stratification (due to higher temperatures obtained within the storage), but mainly has a negative effect on the stratification (Kl).

HEAT-EXCHANGER SIZING

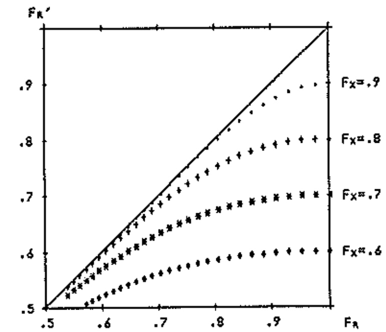
Most of the systems include an external or immersed heat-exchanger between collector and storage. Sizing of the heat-exchanger is somewhat critical. This theory provides some useful information.

Immersed coils generally imply a mixed tank. Losses caused by the heat-exchanger are taken into account by the usual collector-heat-exchanger efficiency factor Fr' whith the limiting value for an infinite flow-rate

$$F_x = 1\ /\ (\ 1 + A\ U_l\ /\ A_eU_e\ ) \tag{6}$$

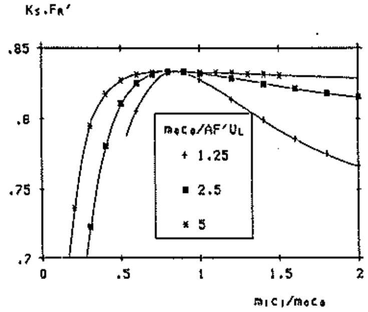
Its variations are represented by fig.2: The lesser of the losses in output from the flow-rate (Fr) and the heat-exchanger (Fx) may be disregarded in practice. At a given flow-rate, a minimum heat-exchanger size is needed but a precise heat transfer coefficient computation is not required. This is an interesting result, if we keep in mind the poor accuracy of such heat-transfer calculation (Feiereisen, 1982).

Fig.2: Collector heat-exchanger correction factor for immersed coils



External heat-exchangers are concerned both with F'r (like immersed coils) and stratification coefficients. The parameter to be considered is their respective product. Fig. 3 shows that for a given primary loop (collector + heat-exch.) there is an optimal flow-rate ratio on both sides of the heat-exchanger for which Fx (eqn 6) is determined again. As for direct systems, flow-rates can be "forgotten", provided they are in a pre-determined ratio, equal to Fx: low flow-rates are compensated by a high degree of stratification (at least one storage cycle is still required). But the optimum flow-rate cannot be determined unless the daily draw-off profile is known.

Fig.3: Optimum flow-rate ratio for an external heat-exchanger



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NOMENCLATURE

A_eU_e	Heat transfer coefficient	m_2	Draw-off flow-rate
H_t	Daily global irradiation	t_d	Collector operating time
m_0	Collector flow-rate	T_m	Mains cold water temperature
m_1	Heat-exch./storage flow-rate	T_0	Storage initial temperature